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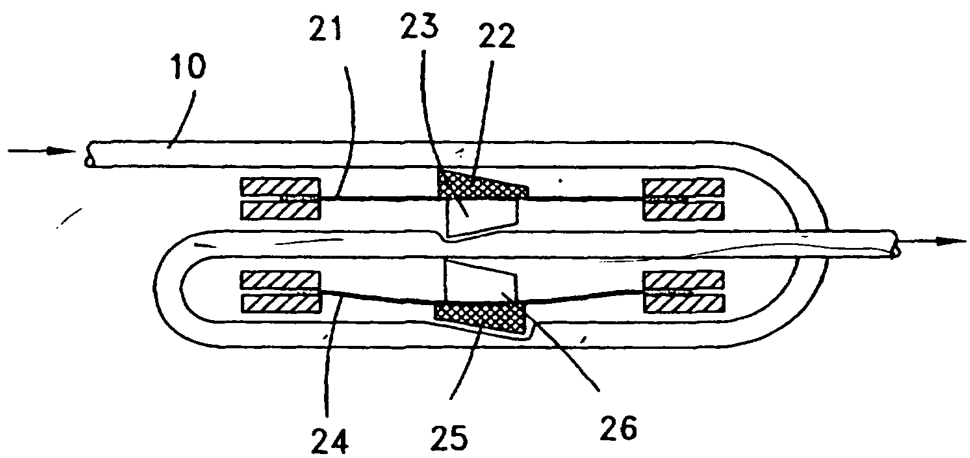
(54) **Title:** PIEZOELECTRIC PUMP



(57) **Abstract:** Peristaltic pump, comprising flexible tube for dispensing liquid, a plurality of piezoelectric actuators disposed across a portion of the tube, for applying pressure on the outside surface of the tube, in order to collapse the surface. The piezoelectric actuators are sequentially activated by timing and control means, to cause sequential collapse of points along the tube surface, thereby causing liquid flow in the tube. Each piezoelectric actuator is attached to pressing element(s), for exerting pressure on the tube upon actuation of the piezoelectric actuators. Each pressing element has a cross-section of an essentially right-angle triangle, one acute angle of which directs to the desired flow direction, in order to force the liquid to flow in that desired direction. In an embodiment of the invention, pairs of pressing elements are arranged face-to-face along a portion of the tube, for simultaneously pressing the portion of the tube between the elements of each pair.

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PIEZOELECTRIC PUMP

Field of the Invention

The present invention relates to peristaltic pumps. More particularly, the invention relates to an improved piezoelectric-based peristaltic pump capable of dispensing small and precise quantities of liquid.

Background of the Invention

Whenever the term "normally closed" is used herein, it refers to a pump in which the liquid channel, or elastic tube, that is used for dispensing liquids, is blocked by means of a diaphragm inhibiting the liquid flow as long as the pump is inactivated.

Whenever the term "normally open" is used herein, it refers to a pump in which the liquid channel, or elastic tube, that is used for dispensing liquids, is unblocked, allowing liquid flow while the pump is inactivated.

Fluid pumping devices have a wide variety of applications and are designed according to specific applications. For example, in medical diagnostic and analysis applications, fluid pumping devices are incorporated into diagnostic systems that require a supply of small and accurate quantities of fluid. The

accuracy of the analysis is (strongly) dependent on the pumping device. Other applications involve administering of drugs to patients, e.g., administering insulin to diabetes patients.

Various micro-pump devices are known in the art of liquid pumps. Generally, they consist of superimposed layers of silicone and glass, as well as piezoelectric elements bonded together. These devices suffer from complex structures, expense and limited usage due to lack of adequate precision. Additionally, pumps of this type are capable of dispensing only small quantities of liquids, limited to the range of *micro-liters/min.* . The reason for such small quantity is the limited elasticity of the glass capillary tube contained in such pumps. However, as science in general, and medicine in particular, evolves, there is an increased need for pumping devices capable of precisely dispensing liquids at larger rates. An improved pump is capable of dispensing wide-ranging volumes of liquids, i.e. up to 650 $\mu liter/\min$..

WO 00/28213 discloses a two-layer pump structure basically comprising a plain sealing layer, an actuation layer, and pump membranes. The dispensing channel disclosed in this publication has a flowing rate smaller than $10\mu l/\min$.. This structure has several drawbacks, one of which is that the channel's membranes may wear rather fast. Another drawback is that

the channel may be blocked due to liquids' residues, which, after emptying the channel from the liquid, tend to solidify.

US 5,927,547 discloses a pump in which the liquid is displaced by the application of pressure around a glass capillary tube by a piezoelectric element, and by virtue of the deformation of the glass. The structure of the pump is very complex, and since the elasticity of the glass membrane is very poor, i.e., its physical movement is in the range of micrometers, this type of pump is capable of dispensing liquids in the range smaller than $10 \mu l / \min$..

US 5,759,015 discloses a pump in which the liquid is displaced by the application of pressure on a diaphragm by a piezoelectric element. This pump does not employ a simple flexible tube to displace the liquid, as is done in the present invention. Furthermore, the liquid displacement chamber is "normally closed". Therefore, this patent suffers from the same drawbacks as WO 00/28213.

Other publications, such as US 4,938,742, US 5,224,843, EP 949418 and SU 1776346, disclose other pumps, in which the structure is either complex, or capable of dispensing liquids only in the micro-liter/minute range.

All of the above prior art pump devices suffer from at least one of the following drawbacks:

(1) The cross-section of the liquid channel is small, in the range of several microns, which may result in obstruction or damage to the pump. Furthermore, if gas bubbles are trapped within the micro-pump, the micro-pump will not function at all, since the presence of the gas bubbles causes an irregular flow;

(2) Complexity of the pump and of the technology required for its manufacturing;

(3) Sensitivity to thermal expansion, and the potential risk of breakage, whenever glass elements are utilized, for example, when a glass capillary tube is used;

(4) Conventional pumps have small capacities. Normally, they are capable of dispensing only very small quantities of liquids, i.e., in the range of pico-liter/minute or micro-liter/minute;

(5) In conventional pumps, at least some of the actuator element(s) are in contact with the dispensed liquid, a fact that may result in contamination of the liquid;

(6) If a same pump is used for dispensing different kinds of liquids, the internal parts of the pump in contact with the liquids must be

thoroughly washed and cleaned, before reusing it to dispense other liquids, in order to eliminate the risk of contamination;

(7) It is practically impossible to replace broken components of these pumps. Therefore, in the event of a broken component, the entire pump must be replaced; and

(8) Conventional pumps that include dedicated "path channel" for dispensing liquids usually require undertaking proper measures in the manufacturing phase, in order to guarantee adequate sealing for preventing leakage.

It is an object of the present invention to provide a pump capable of accurately dispensing liquid.

It is another object of the present invention to provide a simple pump, the rate of which can be easily and dynamically adjusted over a relatively wide range.

It is still another object of the present invention to provide a pump that can be fabricated by using techniques particularly oriented towards mass-production.

It is yet another object of the present invention to provide a pump having a simple and low-cost structure.

Other objects and advantages of the invention will become apparent as the description proceeds.

Summary of the Invention

The present invention relates to a peristaltic pump, which comprises: (a) A flexible tube for dispensing liquids; (b) A plurality of piezoelectric actuators disposed across a portion of the tube for applying pressure on the outside surface of the tube, when actuated, in order to collapse said surface; and (c) Timing and control means for sequentially activating said plurality of piezoelectric actuators, to cause sequential collapse of points along the tube surface, thereby causing liquid flow in the tube.

Preferably, each piezoelectric actuator is attached to at least one pressing element for exerting pressure on the tube upon actuation of the piezoelectric actuator.

Preferably, each pressing element has a cross-section shape of essentially a right-angle triangle.

Preferably, one acute angle α_P of the cross-section triangular shape of each pressing element directs to the desired flow direction, one orthogonal side of

the triangle faces the piezoelectric actuator, and the other orthogonal side to the direction opposite to the desired flow direction.

Preferably, pairs of pressing elements are arranged along a portion of the tube, pressing elements of each pair being arranged face-to-face for allowing them to simultaneously press the portion of the tube, said portion of the tube being between the elements of each pair.

In one embodiment of the invention, two pressing elements are attached to two opposing sides of one piezoelectric actuator, to alternatively exert pressure either by a first of said pressing element on a first portion of said tube when said actuator is in its first state, or by a second of said pressing elements on a second portion of said tube when said actuator is in its second state, and wherein the tube is bent so that two different portions of it being correspondingly in contact with said two pressing elements.

In another embodiment of the invention, each piezoelectric element, when activated, exerts pressure on a fluid in a fluid chamber, and said fluid pushes a piston, which in turn exerts pressure on a portion of the tube surface in order to collapse it and activate flow in the pump.

Preferably, the timing and control means is a microprocessor-based controller.

Preferably, the pump further comprises: (a) driving circuitry, for distributing power for energizing the actuators; and (b) one or more sensors for detecting the liquid flow rate, the information relating to the flow rate being forwarded to said timing and control means, for optimizing the flow rate.

Brief Description of the Drawings

The above and other characteristics and advantages of the invention will be better understood through the following illustrative and non-limitative detailed description of preferred embodiments thereof, with reference to the appended drawings, wherein:

- Figs. 1a-1c schematically illustrate a typical structure of a pump, according to an embodiment of the present invention;
- Figs. 2a-2c schematically illustrate a typical structure of a pump, according to another embodiment of the present invention;
- Figs. 3a-3c schematically illustrate a typical structure of a pump, according to still another embodiment of the present invention;

- Fig. 4 is a block diagram illustrating a system for controlling a pump, according to an embodiment of the present invention; and
- Fig. 5 is a graph showing the relationship between the flow rate and the operating frequency of the pump of Fig. 1.

Detailed Description of Preferred Embodiments

The invention is directed to an improved piezoelectric-based peristaltic pump capable of dispensing precise quantities of liquid at a relatively wide range of flowing rates, said pump preferably comprising a conventional flexible tube, normally open, on which a wave-like pressure is applied at a plurality of points by piezoelectrically-driven pressure elements. By the term “wave-like pressure” is meant a sequential application of pressure at a plurality of points along the liquid dispensing tube.

Among others, the following principles are also implemented in the pump of the present invention:

1) Utilizing a dispensing tube having a relatively large inner diameter, for dispensing drug solutions or other kinds of liquids, with minimum risk of obstruction; and

2) Prohibiting a direct contact between the dispensed liquid and elements of the tube.

Figs. 1A, 1B, and 1C illustrate a structure of a piezoelectric pump, according to one embodiment of the present invention. Fig. 1A illustrates a longitudinal cross-section of the pump. Flexible dispensing tube 10 is placed between a plurality of pairs of piezoelectric actuating elements 13, that are supported by supports 11. To each piezoelectric element 13 is affixed one surface of a pressing element 12 (best shown in detail B). Each pressing element 12 has a cross-section of an essentially right triangle. The surface of the pressing element 12 relating to a first side (generally the longer one) of the right angle of the cross-section triangle is the one affixed to actuating element 13. The second surface of pressing element 12, relating to a side of the right angle of the cross-section triangle, faces the direction of the source of the liquid flow, and the hypotenuse surface faces the flow direction, as is best shown in detail A. An angle of the cross-section triangle is in contact with the outer surface of dispensing tube 10, as shown in detail A. According to the present invention, whenever each pair of parallel piezoelectric elements 13 is actuated, i.e., by supplying to it an exciting voltage, the corresponding pair of pressing elements 12 is driven towards the surface of dispensing tube 10, bending it inwards, thereby forcing the liquid to flow in a direction dictated by the orientation of angle $2*\alpha_P$ (see detail A). For example, as shown in Detail A, the two angles α_P of the two pressing elements 12, when pressed against tube 10, form an 'expulsion angle' of $2*\alpha_P$ to the right hand direction. More particularly, as shown in Fig. 1A,

the angle α_P of each of the two pressing elements 12 faces the right hand direction to keep a consistent unidirectional flow. As described before, the size of angle α_P is determined so as to achieve an optimized liquid flow, and the activation sequence and/or timing of each pair of piezoelectric elements 13 is determined by a microprocessor-based controller (not shown) in accordance with the pump's required flow rate. It should be noted that the timing of the activation of each pair of pressing elements is performed in a sequential manner, in order to produce a wave-like flow.

Figure 1B depicts a cross-section area of dispensing tube 10, piezoelectric elements 13 and corresponding pressing elements 12, and Figure 1C depicts the mechanical housing in which the major elements of the pump are contained. In one embodiment of the invention, the dimensions are, for example, $l=107\ mm$ and $m=32\ mm$.

According to the present invention, a liquid is dispensed through a regular flexible tube, such as a Tygon (or any other silicone-based tube), of which the inner diameter is, for example, 0.5-2 mm. The dispensing tube is placed between parallel actuator elements. A piezoelectric element is normally in the form of a disk, with a diameter of, for example, $\Phi = 30mm$ and thickness of $0.4mm$. However, a piezoelectric element of almost any type/form may be utilized as an actuator. These pairs of actuator elements are aligned

essentially along a longitudinal line to render the spacing between each two consecutive pairs essentially equal.

As said, to each piezo-electric actuating element is affixed one surface of a pressing element. The cross-section of the pressing element is essentially a right triangle. Another part of the pressing element is pushed, upon actuation, against an outer surface of the dispensing flexible tube. Each pressing element has an angle α_P such that $0^\circ < \alpha_P << 90^\circ$, and a same angle exists between the hypotenuse of the cross-section triangle and the longitudinal axis of the tube. Therefore, two face-to-face pressing elements attached to corresponding parallel piezoelectric actuators create an angle that is as twice that created by one pushing element, i.e. $2 * \alpha_P$.

Each two piezoelectric actuator elements forming a pair are simultaneously activated. Whenever activated, each pair of actuator elements exerts pressure via the pressing elements on the outer face of the dispensing tube. Since the pressing elements are driven each against the other, and the flexible tube is placed in between, the exerted pressure causes the elastic surface of the dispensing tube to press and bend inwards.

Coordinating the activation of the actuator elements is carried out by a controller, one task of which is to allow determining the supply rate of the

pump, i.e., by allowing controlling the parameters of the pumping 'sequence'/'cycle', and another task of which is translating the total required quantity of the dispensed liquid into the corresponding number of cycles. The controller is capable of changing the capacity of the pump within a rather large range of capacities (e.g. from several picoliters to hundreds of microliters). Moreover, the capacity of the pump disclosed herein may be changed, automatically or manually, while the pump is dispensing liquid(s).

Figs. 2A, 2B, and 2C illustrate a structure of a pump, according to another embodiment of the present invention. The pump of this embodiment is more economical with respect to the pump of Fig. 1, as it requires half the number of piezoelectric elements; in this case, only two piezoelectric elements (21 and 24) drive four pressing elements (22, 23, 25 and 26). Fig. 2A depicts the pump in its initialized, 'rest' state. In the rest state, the piezoelectric elements 21 and 24 are inactivated so that pressing elements 23 and 26 act essentially as a valve in its 'close' state, thereby inhibiting liquid flow. In order to activate the pump, a voltage is applied to piezoelectric element 21, which causes it to bend (Fig. 2B), thereby achieving simultaneously two effects: opening and allowing a liquid flow in the middle section 70 of tube 10 by lifting pressing element 23, and generating a pushing force on the liquid contained in dispensing tube 10 by pushing pressing element 22 against the wall 71 of tube 10. The next step of the pump is the inactivation of piezoelectric element 21 and the activation of piezoelectric element 24,

thereby causing piezoelectric element 21 to return to its initial position and piezoelectric element 24 to bend (see 2C), thereby achieving similar effects to those described with respect to the state of Fig. 2b. Namely, the valve is kept open (now by pressing element 26), and the liquid is pushed further by pressing element 25. A normal operation of such a pump involves intermittently activating piezoelectric elements 21 and 24 by supplying voltage to each of them in turn. Referring to 2A, the dimensions of the pump may be, for example, l=*42 mm*, m=*42 mm* and n=*27 mm*.

Figs. 3A, 3B, and 3C illustrate a structure of a piezo-hydraulic pump, according to another embodiment of the present invention. The pump has only one piezoelectric element 31, two opposing sides of which are connected to moveable membranes, such as membranes 32 and 33. One operation cycle of this pump involves piezoelectric element 31 being in three different states, at three different times. In the first state the piezoelectric element is inactivated (i.e., no voltage is supplied to it), in the second state it is supplied with a positive voltage, and in the third state it is supplied with a negative voltage. The three pairs of piezoelectric elements (13) and corresponding pressing elements (12) of the embodiment of Fig. 1 are replaced in the embodiment of Fig. 3 by three hydraulic tubes and three pistons (37, 38 and 39). One operating cycle of this pump essentially comprises the following steps:

1) Step one (see Fig. 3A) – no voltage is supplied to piezoelectric element 31. Consequently, it retains the initial state, in which the inlet of the pump is blocked by piston 39, while two other pistons 37 and 38 exert no pressure on dispensing tube 10. It should be noted that despite the fact that the volume of each of chambers 35 and 36 is smaller now with respect to the volume in step one (Fig. 3a), only piston 39 exerts pressure on dispensing tube 10. The reason for this is that tube 35a has a larger diameter than that of tube 36a. Therefore, despite the fact that essentially the same amount of hydraulic fluid is discharged from chambers 35 and 36, piston 39 travels a longer distance than piston 38.

2) Step two (Fig. 3B) – a positive voltage (not shown) is supplied to piezoelectric element 31, causing it to expand. Consequently, piston 38 exerts pressure on dispensing tube 10. In this step piston 39 is still blocking the inlet side of tube 10 and prevents liquid from flowing 'backwards'. Therefore, piston 38, by exerting pressure on tube 10, causes the liquid to flow in the other direction, i.e., to the outlet of tube 10.

3) Step three (Fig. 3C) – a negative voltage (not shown) is supplied to piezoelectric element 31, which causes it to be in its contracted state, wherein hydraulic liquid is pushed out from chamber 34 so as to elongate piston 37, thereby blocking the outlet of dispensing tube 10. Contraction of piezoelectric element 31 also causes chambers 35 and 36 to increase

their volume, thereby causing pistons 38 and 39 to withdraw and release any pressure from dispensing tube 10, thereby allowing it to be filled with supplement liquid before the next cycle begins.

It should be noted that other modes for operating the pump might be utilized. For example, one operating cycle of the latter pump might comprise only the above-mentioned steps 2 and 3.

The present invention is therefore characterized by the following novel features: The first feature is the utilization of the dispensing tube itself as part of the piezoelectric pump, i.e., as an integral dispensing channel. This feature stands in contrast to prior art piezoelectric pumps, wherein a special/dedicated dispensing channel exists in the pump, in order to be utilized as a dispensing tube/line. The second novel feature is affixing pressing elements having a unique shape, i.e., preferably a right-angle triangle, to piezoelectric actuator elements, through which pressure is applied to the flexible tube, thereby achieving a better fluidity of liquid.

Fig. 4 schematically illustrates a general layout and functioning of a system for controlling the pump of Fig. 1. The piezoelectric elements (not shown) of pump 41 are connected to voltage excitation distributor 42 that transfers the voltage required for the functioning of each pair of piezoelectric elements at the right time. Power supply 43 is the voltage source for both

the voltage excitation distributor and for controller 44 (generally a microprocessor), and it is capable of supplying positive and negative voltages required for activating the pumps, such as depicted in Figs. 1, 2 and 3. Microprocessor-based controller 44 determines the activation timing of each piezoelectric element, as set by the pump operator/user.

Fig. 5 is a graph showing the relationship between the flow rate of the pump of Fig. 1, and the operating frequency of the pump, according to a test conducted by the inventors. The testing procedure was carried out by utilizing a flexible dispensing tube having an inner diameter of *1mm* and a wall thickness of *0.5mm*. The pump functioning was tested by dispensing three different liquids, i.e., Water, Insulin and Oil, of which dispensing rate q (in micro-liter per minute) versus the operating frequency of the pump (in Hertz) has been recorded.

<u>Some of the advantages of the present invention</u>:

The present invention is characterized in that the pressing elements are pushed directly against the outer face of the flexible dispensing tube, thereby solving many problems of the prior art devices. The structure of the micro-pump disclosed herein is very simple, since, unlike most of the prior art pumping devices, it does not contain sealing layers, glass elements, membranes or valves. Such elements are not required in the pump of the

present invention, since the elasticity characteristics of portions of the dispensing tube are utilized as membrane substitutes. This is advantageous since whenever the elasticity of the portion becomes poor, the pump can be moved so as to press another portion of the tube.

While some embodiments of the invention have been described by way of illustration, it will be apparent that the invention can be carried into practice with many modifications, variations and adaptations, and with the use of numerous equivalents or alternative solutions that are within the scope of persons skilled in the art, without departing from the spirit of the invention or exceeding the scope of the claims.

CLAIMS

1. A peristaltic pump, comprising:

a) A flexible tube for dispensing a liquid;

b) A plurality of piezoelectric actuators disposed across a portion of the tube for applying pressure on the outside surface of the tube, when actuated, in order to collapse said surface; and

c) Timing and control means for sequentially activating said piezo-electric actuators, to cause sequential collapse of points along the tube surface, thereby causing liquid flow in the tube.

2. A peristaltic pump according to claim 1, wherein each piezoelectric actuator is attached to at least one pressing element.

3. A peristaltic pump according to claim 2, wherein each pressing element has a cross-section shape of essentially a right-angle triangle.

4. A peristaltic pump according to claim 3, wherein one acute angle α_P of the cross-section triangular shape of each pressing element directs the desired flow direction, one orthogonal side of the triangle faces the piezoelectric actuator, and the other orthogonal side to the direction opposite to the desired flow direction.

5. A peristaltic pump according to claim 3, wherein pairs of pressing elements are arranged along a portion of the tube, each pair of pressing elements being arranged face-to-face to allow them to simultaneously press the portion of the tube, said portion of the tube being between said elements of each pair.

6. A peristaltic pump according to claim 3, wherein two pressing elements are attached to two opposing sides of one piezoelectric actuator, to alternatively exert pressure either by a first of said pressing element on a first portion of said tube when said actuator is in its first state, or by a second of said pressing elements on a second portion of said tube when said actuator is in its second state, and wherein the tube is bent so that two different portions of it are correspondingly in contact with said two pressing elements.

7. A peristaltic pump according to claim 1 wherein each piezoelectric element, when activated, exerts pressure on a fluid in a fluid chamber, and said fluid pushes a piston, which in turn exerts pressure on a portion of the tube surface in order to collapse it and activate flow in the pump.

8. A peristaltic pump according to claim 1, wherein the timing and control means is a microprocessor-based controller.

9. A peristaltic pump according to claim 1, further comprising:

a) Driving circuitry, for distributing power for energizing the actuators; and

b) One or more sensors for detecting the liquid flow rate, the information relating to the flow rate being forwarded to said timing and control means, for optimizing the flow rate.

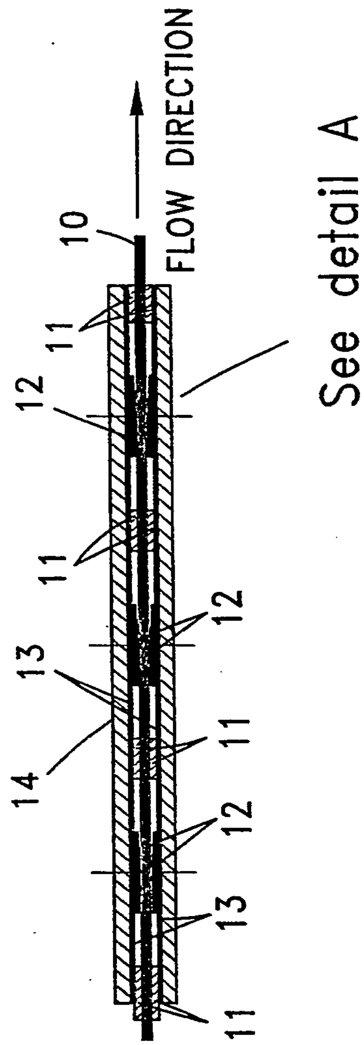


Fig.1A

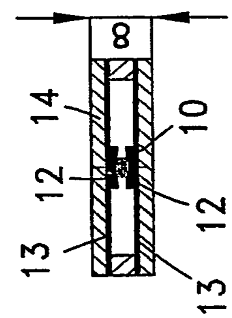
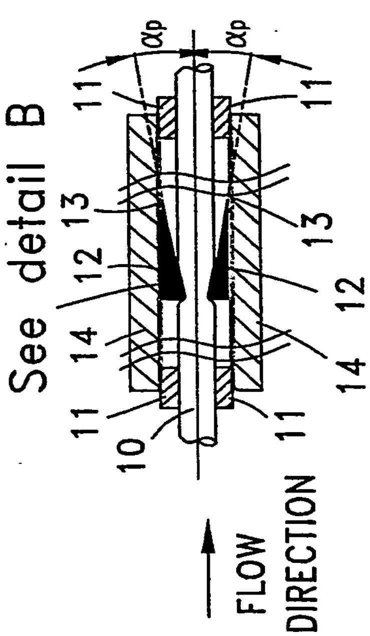
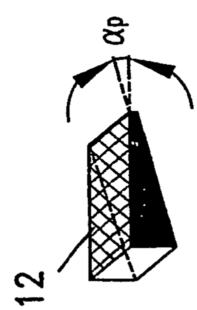


Fig.1B



Detail A



Detail B

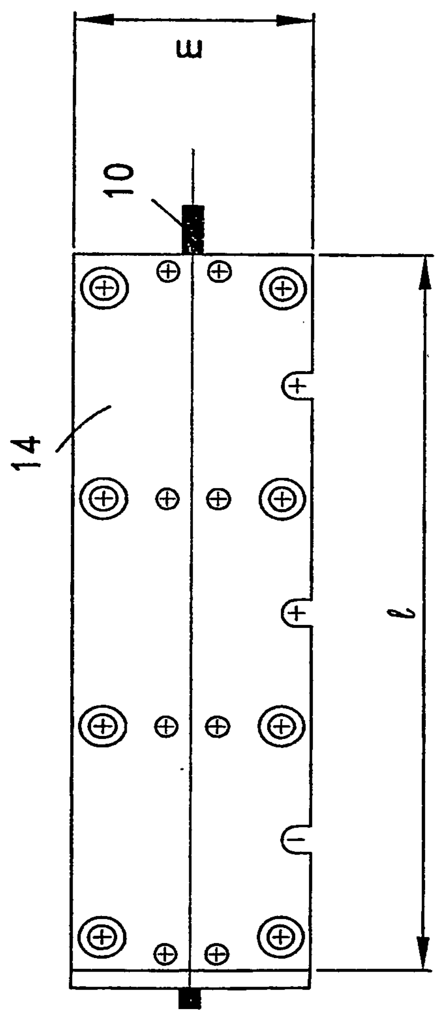


Fig.1C

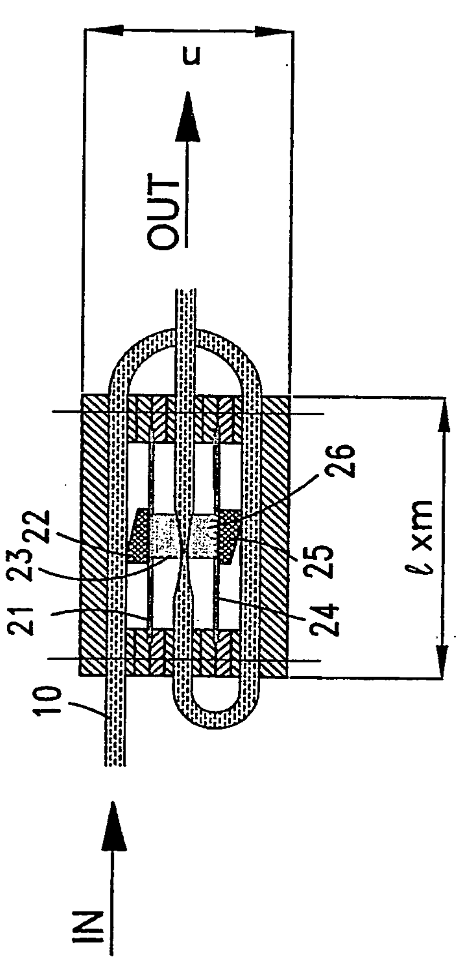


Fig. 2A

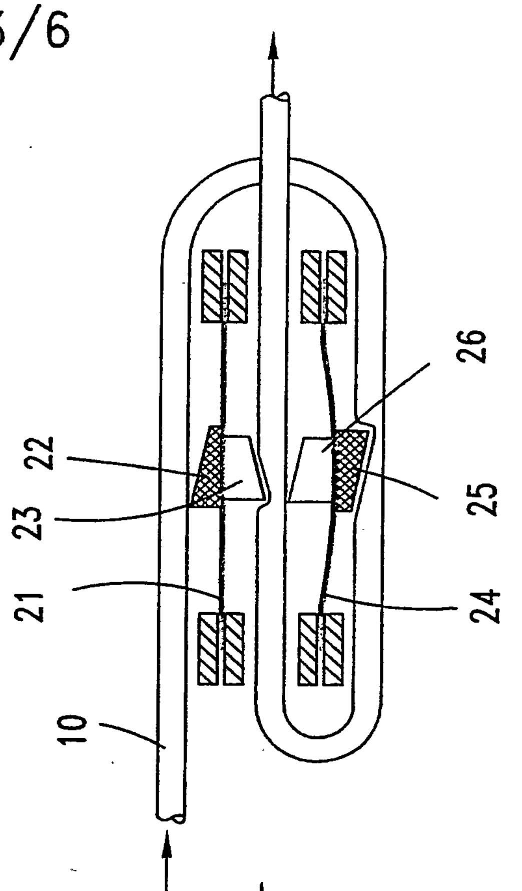


Fig. 2C

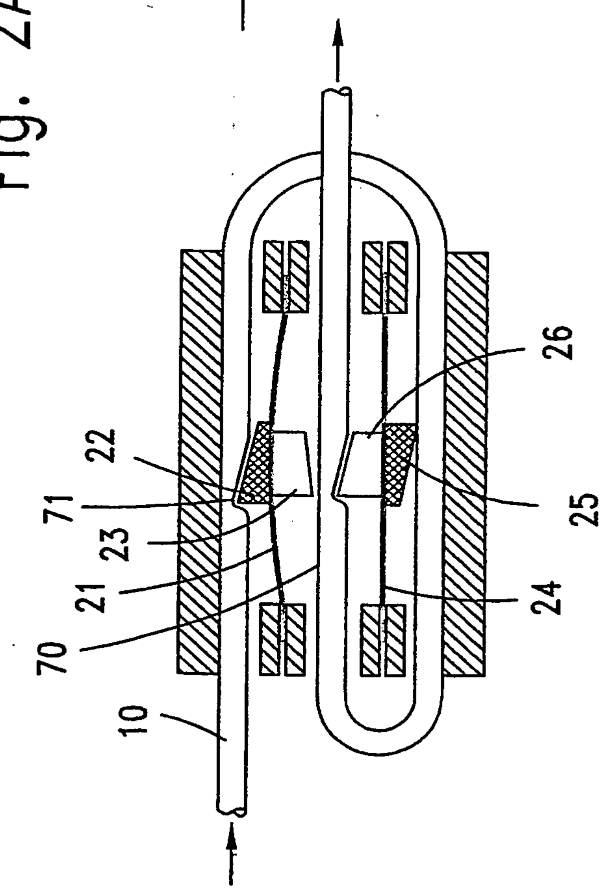


Fig. 2B

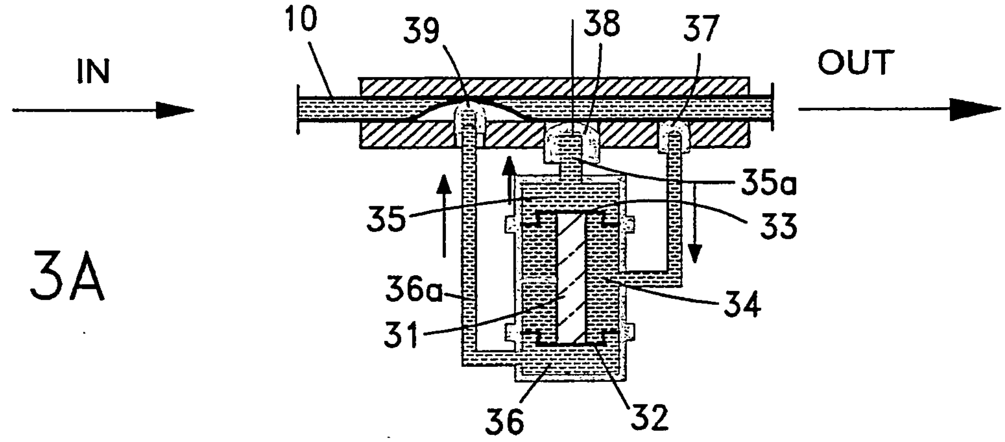


Fig. 3A

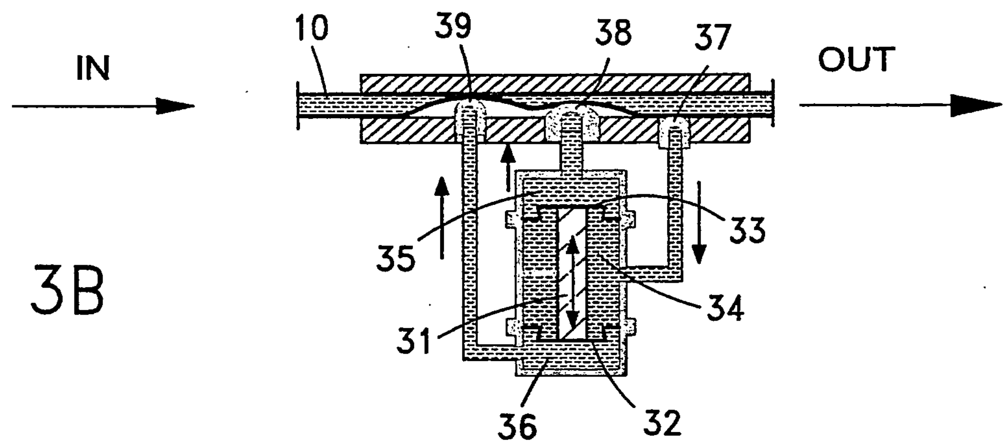


Fig. 3B

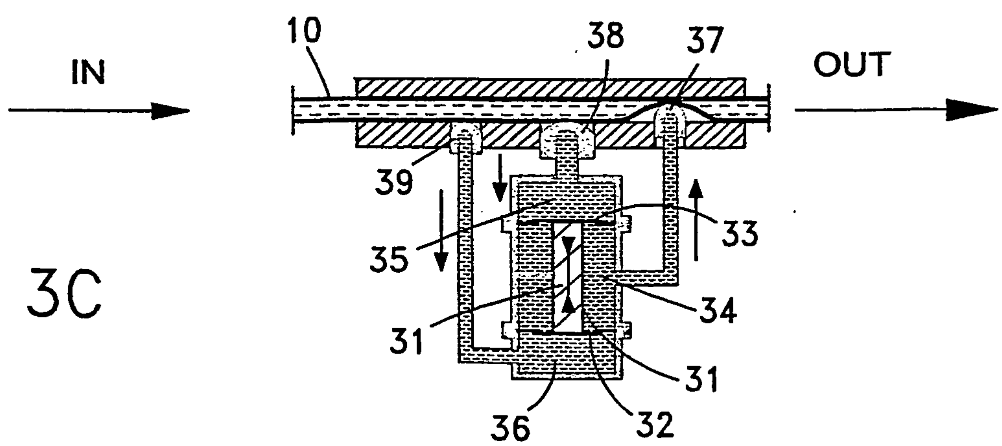
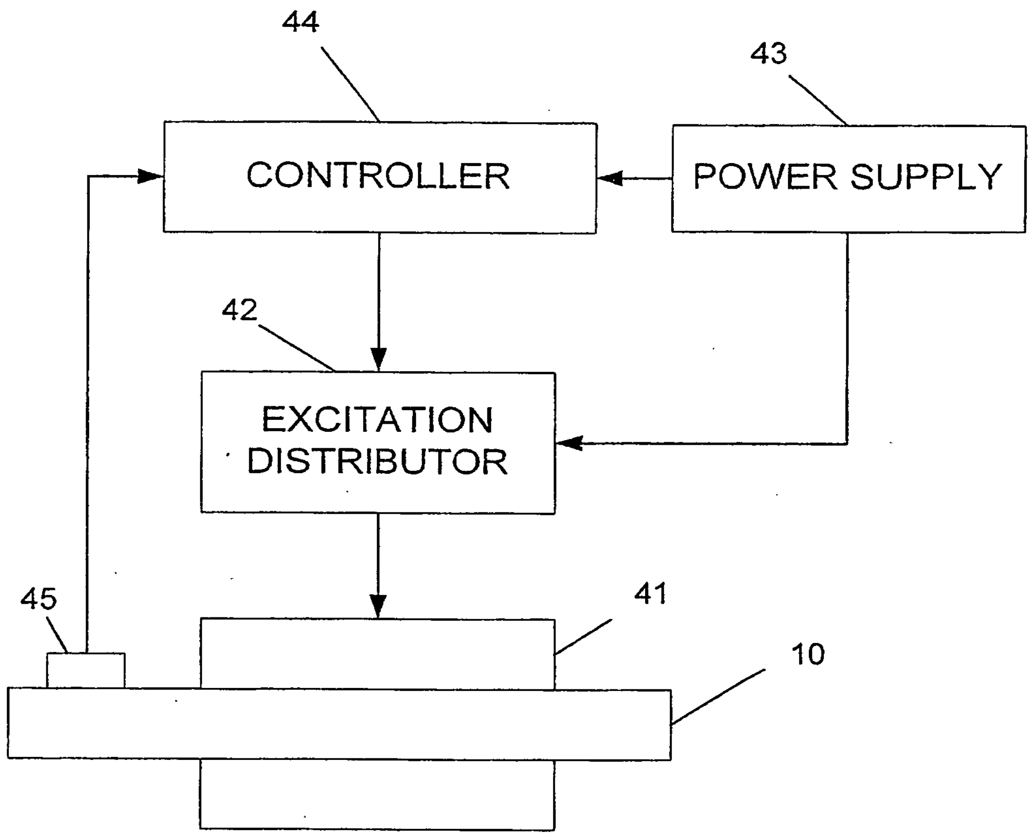


Fig. 3C



44
43
CONTROLLER
POWER SUPPLY
42
EXCITATION DISTRIBUTOR
45
41
10

Fig. 4

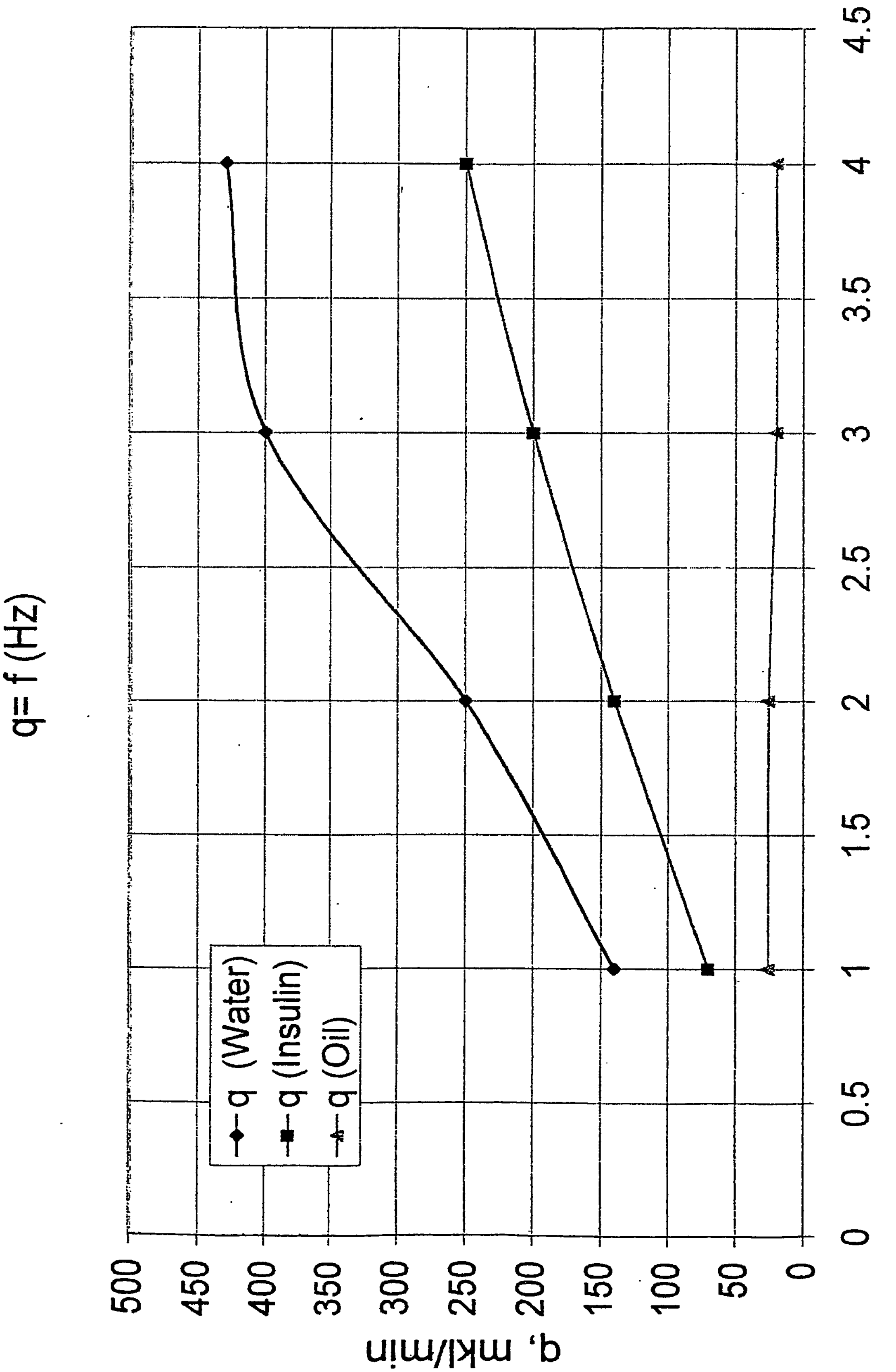

q= f (Hz)
q, mkl/min
500
450
400
350
300
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Hz
q (Water)
q (Insulin)
q (Oil)

Fig. 5

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IL 02/00756

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 F04B43/04 F04B43/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 F04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 97 42412 A (BERTONY JOSEPH ;PUMPING SYSTEMS TECHNOLOGIES P (AU)) 13 November 1997 (1997-11-13) page 8, line 8 -page 9, line 9; figures 1,8	1,2,8,9
Y	abstract; claim 23	3-7,9
X	JP 03 107585 A (FUJITSU LTD) 7 May 1991 (1991-05-07) abstract; figure 1	1,2,8
Y	FR 2 337 824 A (VIAL SARL) 5 August 1977 (1977-08-05) page 2, line 16 -page 4, line 28; figures	3-6

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
28 November 2002	27/12/2002

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Pinna, S

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IL 02/00756

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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A Y	EP 1 031 358 A (FRESENIUS VIAL SA) 30 August 2000 (2000-08-30) abstract	1-8 9
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[illegible]rmation on patent family members

Inte[illegible]al Application No
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